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ON THE IONIZING EFFICIENCY OF METEORS

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Summary

This paper reviews the present knowledge on the ionizing efficiency of meteors, τ_q . There is a considerable measure of disagreement among authors both concerning its order of magnitude and concerning its dependence on the velocity. Since the luminous efficiency, τ_p , is known with a fair degree of accuracy, we have evaluated the ionizing efficiency from τ_p and from Millman and McKinley's data relating durations of radio echoes and visual magnitudes. We find the ionizing efficiency proportional to v^2 and the probability, β , that an atom ablated from a meteoroid will produce a free electron proportional to v^4 . From the results of the simultaneous photographic and radio observations of meteors by Davis and Hall and from the value of τ_p , we find $\beta = 0.01$ at $v = 32 \text{ kms}^{-1}$. Accordingly, we obtain $\beta = 1 \times 10^{-20} v^4$ and $\tau_q = 6 \times 10^{-13} v^2$, with v expressed in ms^{-1} . The comparison of the rates of photographic and radio meteors of about the same magnitude confirms the proportionality $\beta \sim v^4$. As a consequence, the relation between the magnitude and the electron line density of the trail is independent of the velocity.

On the Ionizing Efficiency of Meteors

Franco Verniani¹ and Gerald S. Hawkins²

Introduction

The luminous and ionizing efficiencies of meteors are quantities of paramount importance for meteor physics, because each of them is necessary, depending on the technique employed for the observations, to evaluate masses and densities of meteoroids. Nevertheless these quantities are far from being known with the needed accuracy because of the serious difficulties of both a comprehensive theoretical study and an experimental or observational approach.

The meteor ionizing efficiency τ_q is defined as the ratio between the power I_q going into the production of electrons and the rate of loss of the kinetic energy of the atoms ablated from the meteor body.

$$I_q = - \frac{1}{2} \tau_q v^2 \frac{dm}{dt}, \quad (1)$$

v and m being velocity and mass of the meteor. The luminous efficiency is defined by an equation analogous to eq. (1). It is convenient to consider two different luminous efficiencies τ_v and τ_p , relating to the visual luminous intensity I_v and the photographic luminous intensity I_p , which is defined by the sensitivity of the blue emulsion generally used in Harvard photographic studies.

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The present knowledge on the luminous efficiency has been discussed elsewhere by Verniani (1964), who computed the quantity τ_p/ρ_m^2 (ρ_m = meteoric density) for about 400 Super-Schmidt meteors that were precisely reduced by Jacchia (unpublished). He found that the variation of τ_p with the velocity both for bright and faint meteors was represented by the linear law $\tau_p = \tau_{op} v$. The value of τ_{op} turned out to be $5.2 \times 10^{-8} \text{ m}^{-1}\text{s}$, which agrees very well with the value inferred by McCrosky and Soberman (1962) from observations of an artificial meteoroid. The uncertainty in the value of τ_{op} was estimated to be of the order of 2, while the probable error of the velocity exponent was ± 0.15 . Since the ionizing efficiency τ_q is known with less certainty, it seems reasonable to try to deduce the value of τ_q from the known values of τ_p and τ_v .

Instead of τ_q we often use the ionizing probability of a meteor atom β , which is a dimensionless quantity, as is τ_q . It is easily seen that the relation

$$\tau_q = \frac{2\Phi}{\mu v^2} \beta \quad (2)$$

holds when μ is the mass of a meteor atom and Φ , the corresponding ionization energy. Estimates of the average value of β have been made by Herlofson (1948), McKinley (1951), Greenhow and Hawkins (1952), Kaiser (1953), Evans and Hall (1955) and Davis and Hall (1963). The results range from 10^{-2} to 1 except for McKinley's, which are much smaller because the difference between underdense and overdense trails was not known at that time and this led to an underestimate of the electronic line density of the trail and consequently of β .

Theoretical determinations of the ionizing probability β have been done by Öpik (1958) and by Lazarus and Hawkins (1963). Their results differ by two orders of magnitude. As Öpik's computation is based on many questionable assumptions, it is impossible to estimate the reliability of his results. He gives the ionizing probability β_{Fe} for iron meteors; his results are listed in Table 1. In the same table we give the average values of β for cometary meteors obtained from β_{Fe} by following the

assumptions of Lazarus and Hawkins. The ionization probabilities of different elements are taken to be proportional to $n_v \mu Z^{-6}$, where n_v is the number of valence electrons available for ionization, and it is assumed that meteors have the same abundance of elements as stone meteorites. Then the average value of β is equal to $0.345 \beta_{Fe}$. Lazarus and Hawkins (1963) have computed the ionization cross section for the sodium atom colliding with an oxygen atom. With the above assumptions they determined the value of β for meteors. If we assume a power-law dependence on v for β , then we can write

$$\beta = \beta_0 v^{\eta} . \quad (3)$$

The results of Lazarus and Hawkins can be approximately represented by

$$\beta = 1.3 \times 10^{-19} v^{3.4} , \quad (4)$$

with v expressed in ms^{-1} *. This value of β is uncertain because of lack of knowledge of the chemical composition of the meteoroid. The dependence of β on the velocity is not at all well known. The estimates of the exponent η of the law $\beta \sim v^{\eta}$ range from zero to 6.

The ratio τ_v/β can be evaluated from observations of the duration of radar echoes from overdense trails and of the visual magnitude of the corresponding meteors. The first to use such a method were Greenhow and Hawkins (1952), but the lack of observational data compelled them to consider both τ_v and β as independent of velocity. The method was later resumed by Hawkins (1956), who found $\tau_v/\beta \sim v^{-4.56}$, i.e., $\beta \sim v^{5.6}$. The same method was also used by Evans and Hall (1955) with data similar to those of Hawkins. Their estimate** was $\tau_v/\tau_q \sim v^{-1}$, i.e., $\beta \sim v^4$, but they preferred to conclude $\eta = 0.5 \pm 0.5$ on the basis of the gradient of the height-versus-velocity curve. This last result seemed to confirm a

* We shall use mks units throughout the paper.

**As Hawkins (1956) pointed out, their data lead actually to $\tau_v/\tau_q \sim v^{-3}$, i.e., $\beta \sim v^5$.

previous estimate of Kaiser (1953), who found $\eta = 0 \pm 0.6$ from Jodrell Bank's radio data. Evans and Hall, however, did not consider the variation of the zenith angle of the path and of the electronic density with the meteor height, so their results appear unreliable. Davis, Greenhow and Hall (1959a) studied the effects of attachment on the duration of radio echoes and applied their conclusions to Millman's and McKinley's (1956) data correlating visual magnitude and duration of echoes. They concluded that $\tau_v/\tau_q \sim v^{0 \pm 1}$, i.e., $\beta \sim v^{3 \pm 1}$. Their procedure of correcting the observational data for attachment has been criticized by McKinley (1961), who re-examined his own data and concluded that $\tau_q/\tau_v \sim v^2$, i.e., $\beta \sim v^5$. Whipple (1955) reached an independent estimate of the value of η by comparing the rates of photographic and radio meteors. He found $\beta \sim v^5$.

Table 2 summarizes all the previous estimates of β . Even if we disregard the results of Kaiser and of Evans and Hall, the estimates of the exponent η range from 3.4 to 5.6. Thus if we take a fixed value of β at $v = 10 \text{ kms}^{-1}$, the uncertainty at 70 kms^{-1} is two orders of magnitude. Such large disagreement led us to reconsider the evaluation of τ_v/β on the basis of the most recent data.

The determination of τ_v/β from the correlation between visual magnitude and the duration of the meteoric radio echoes

We will divide our investigation into two parts. First we will determine η in eq. (3), then we will determine β_0 . This procedure is necessary because of the nature of the observational data. To determine η we require homogeneous observations at different velocities, but to determine β_0 we can use the average of more accurate measurements.

The absolute visual magnitude M_v of a meteor radiating I_v watts in the spectral region 4500 to 5700 Å has been expressed by Öpik (1958) in the form:

$$M_v = 6.8 - 2.5 \log I_v . \quad (5)$$

The uncertainty in the constant 6.8 of eq. (5) could be avoided by using zero magnitude units for I_v . However, this uncertainty does not at all affect the final results for β .* The visual luminous intensity I_v is given by an equation analogous to eq. (1):

$$I_v = -\frac{1}{2} \tau_v v^2 \frac{dm}{dt} . \quad (6)$$

The electronic line density q along the meteor trail is given by:

$$q = - \frac{\beta}{\mu v} \frac{dm}{dt} ; \quad (7)$$

thus, by eliminating $\frac{dm}{dt}$ between eqs. (6) and (7) and by using eq. (5), we get

$$M_v = 6.8 - 2.5 \log \left(\frac{\mu}{2} \frac{\tau_v}{\beta} v^3 q \right) . \quad (8)$$

The average atomic weight of a meteor atom, according to Öpik (1958), is 23; therefore $\mu = 3.82 \times 10^{-26}$ kg. If we introduce this value of μ into eq. (8), the equation becomes

$$M_v = 71.10 - 2.5 \log \frac{\tau_v}{\beta} - 7.5 \log v - 2.5 \log q . \quad (9)$$

The duration T_D of a radio echo from a meteor trail with $q > 10^{14}$ electrons/m, considering the effect of diffusion alone, is given by the expression (Kaiser and Closs 1952, Greenhow 1952)

$$T_D = \left(\frac{\mu_0 e^2}{16\pi^3 m_0} \right) \frac{\lambda^2}{D} q , \quad (10)$$

e and m_0 being the electric charge and the rest mass of the electron; μ_0 , the magnetic permeability of the empty space; λ , the wavelength of the radar; and D , the ambipolar diffusion coefficient at the height of the reflecting section of the trail. Since we will use the observational data of Millman and McKinley (1956), obtained at a frequency of 32.7 Mc s^{-1} ,

* To convert the mks values of τ_v and τ_p to units of zero magnitude (0 Mag $\text{kg}^{-1} \text{m}^{-2} \text{s}^3$) one must divide by 525.

we have

$$\log T_D = -14.222 + \log q - \log D . \quad (11)$$

The most reliable values of the diffusion coefficient D as a function of the height z are given by the experimental results of Greenhow and Hall (1961), which can be expressed approximately by the relation

$$\log D = 5.43 \times 10^{-5} z - 4.373 . \quad (12)$$

By substituting eqs. (11) and (12) into eq. (9) we obtain

$$M_V = 46.475 - 2.5 \log \tau_v/\beta - 7.5 \log v - 2.5 \log T_D - 1.36 \times 10^{-4} z. \quad (13)$$

Millman and McKinley (1956) give observations of Perseids, Geminids, δ -Aquarids and sporadic meteors. These data are summarized in Table 3. We will not consider the δ -Aquarids, since, as the authors pointed out, the data are insufficient.

By inserting the observed data into eq. (12) we obtain the following values of $\log \tau_v/\beta$:

$$\left. \begin{array}{l} \text{Perseids: } \log \tau_v/\beta = -2.018 \\ \text{Geminids: } \log \tau_v/\beta = -1.259 \\ \text{Sporadic: } \log \tau_v/\beta = -1.559 \end{array} \right\} . \quad (14)$$

These values of $\log \tau_v/\beta$ must be reduced to the same magnitude, since the coefficient τ_{ov} of the law $\tau_v = \tau_{ov} v$ varies with visual magnitude (Verniani 1964), according to the relation

$$\log \tau_{ov} = -8.02 + 0.156 M_V , \quad (15)$$

where $-2 < M_V < +1.5$. By reducing the computed values of $\log \tau_v/\beta$ to zero visual magnitude we obtain:

$$\begin{array}{lcl}
 \text{Perseids: } \log \tau_v/\beta = -2.080 & \left. \vphantom{\begin{array}{l} \text{Perseids: } \log \tau_v/\beta = -2.080 \\ \text{Geminids: } \log \tau_v/\beta = -1.381 \\ \text{Sporadic: } \log \tau_v/\beta = -1.750 \end{array}} \right\} & . \quad (16) \\
 \text{Geminids: } \log \tau_v/\beta = -1.381 & & \\
 \text{Sporadic: } \log \tau_v/\beta = -1.750 & &
 \end{array}$$

Let us now consider the effects of attachment. The relation between the echo duration T in the presence of both diffusion and attachment and the echo duration T_D in the presence of diffusion alone is (Davis, Greenhow and Hall 1959b)

$$T_D = T \exp (\beta_e n_m T), \quad (17)$$

where β_e is the coefficient of electron attachment and n_m is the density of neutral molecules capable of forming negative ions. There is some dispute about the value of $\beta_e n_m$. Davis, Greenhow and Hall (1959b) found that the value $\beta_e n_m = 0.025 \text{ s}^{-1}$ at $z = 95 \text{ km}$ best fitted their observations of a bright Geminid. The uncertainty in this value was of the order of a factor of 2. The same authors (1959a) later concluded from the analysis of the data of Millman and McKinley (1956) that a reduction of the previous value by a factor of $2/3$ could improve the agreement between theory and observations. This conclusion has been criticized by McKinley (1961), who found on the basis of the same data $\beta_e n_m = 0.0065 \text{ s}^{-1}$ as the best fit and excluded the possibility $\beta_e n_m > 0.01 \text{ s}^{-1}$. Otherwise the theoretical maximum duration of the radio echoes could not be more than 5 minutes, whereas durations of 30 minutes or even longer have been recorded. As a compromise we will assume $\beta_e n_m = 0.01 \text{ s}^{-1}$. Equation (17) therefore becomes

$$\log T_D = \log T + 0.0043 T. \quad (18)$$

By correcting the observed durations by means of eq. (18), we obtain our final values:

$$\left. \begin{array}{l} \text{Perseids: } \log v = 4.782; \log \tau_v/\beta = -2.155 \\ \text{Geminids: } \log v = 4.548; \log \tau_v/\beta = -1.450 \\ \text{Sporadic: } \log v = 4.653; \log \tau_v/\beta = -1.792 \end{array} \right\} \quad (19)$$

These results are plotted in Figure 1. A least-squares solution gives*

$$(\log \tau_v/\beta)_{M_v=0} = (12.2 \pm 0.1) - (3.0 \pm 0.1) \log v, \quad (20)$$

which leads to

$$\tau_v/\beta = 1.5 \times 10^{12} v^{-3}. \quad (21)$$

It is interesting to note that the correction for attachment does not appreciably affect the value of the exponent, while the value of τ_v/β has been decreased by a few percent. According to eq. (15) the visual luminous efficiency at $M_v = 0$ is given by

$$\tau_v = 9.5 \times 10^{-9} v; \quad (22)$$

thus we obtain for β :

$$\beta = 6.3 \times 10^{-21} v^4. \quad (23)$$

Observational data correlating visual magnitude and radio echo durations of Perseids have also been published by Lindblad (1963). From this author we quote:

$$\bar{M}_v = +1.0; \overline{\log T} = 0.532; \bar{T} = 10.96 \text{ s}; \log T_D = 0.580. \quad (24)$$

* A least-squares solution with weights proportional to the number of meteors of each group gives the constants as 12.0 ± 0.1 and -2.9 ± 0.1 .

The value of $\log \tau_v/\beta$, after we correct for attachment and reduce to $M_v = 0$, is -2.281 . This result is in reasonable agreement with equations (21) and (23).

Criticisms on the present method have been made by Davis and Hall (1963), who remark that visual magnitude estimates are probably a function of the apparent angular velocity of a meteor and therefore are not reliable. The color index of about 300 Super-Schmidt meteors did not, however, show any dependence on velocity (Jacchia 1957). The independence of color index on velocity has been confirmed by the analysis of all Super-Schmidt meteors reduced by Jacchia (unpublished). Therefore there is no detectable error resulting from angular velocity. Davis and Hall also argue that the use of data concerning different showers is not valid because of the possible differences in the composition of meteors. Actually τ_v/β is proportional to the average atomic mass μ and therefore depends on the chemical composition of meteors. Although differences in density and strength among meteors of different showers have been found (Jacchia 1956, 1963; Verniani 1964), an appreciable change in μ does not seem possible. In fact, differences in densities among meteors of different showers can be explained, according to Whipple's theory (1950, 1951) of the icy comet, by differences in the ages of the parent comets. Dense meteors originate from the inner core of old comets, while meteors of normal density come from more external layers. The composition may be the same, but the difference in pressure to which the different parts of the comet were subjected is responsible for the difference in density.

McKinley found $\beta \sim v^5$ from the same data that lead us to conclude $\beta \sim v^4$. This difference can be ascribed to three causes: 1) McKinley used the early results of Greenhow and Neufeld (1955) for the ambipolar diffusion coefficient D ,

$$\log D = 6.7 \times 10^{-4} z - 5.6, \quad (25)$$

instead of our eq. (12). 2) No correction was applied for reducing τ_v to a fixed magnitude. 3) The correlation between M_v and $\log T$ was assumed to be of the form

$$\log T = \text{const.} - 0.4 M_v. \quad (26)$$

Equation (26) would be true only if the meteor height did not depend on the magnitude or on the electronic density q . It is easily found, as McKinley also points out, that the maximum duration T_m , occurring when the reflecting point coincides with the point of maximum electron density, is related to M_v by

$$\log T_m = \text{const.} - 0.533 M_v. \quad (27)$$

A similar relation probably also holds for $\log T$. In this paper we have directly substituted the observational values in eq. (13) and thus avoided the problem of the slope of the curve $\log T$ vs. M_v .

Let us now discuss the accuracy of the present method for determining β_o . The echo is generally not obtained from the point of maximum light to which the magnitude refers. This can lead to an underestimate of the value of β of perhaps 50 percent. Therefore we will find the value of β_o by another method. It is unlikely, however, that it can affect the value of η . There are also some doubts on the reliability of eq. (10), in which the duration T_D is independent of the transmitting power of the radar. McKinley's (1953a) observations using two radars of different power show a dependence of duration on power. This evidence is not conclusive, however, because one cannot exclude the possibility that the low-power echoes come from underdense trails while the high-power echoes certainly come from overdense trails. The proportionality between T_D and λ^2 has also been questioned, and a much more complicated relation has been proposed by McKinley (1953b). The experimental results of Davis, Greenhow and Hall (1959a) show, however, that for the durations used in eq. (13) such proportionality is still valid.

We have chosen to use the observations of Davis and Hall (1963) to determine the value of β_0 . These authors determined the ratio I_p/q for 7 meteors observed simultaneously by radar and by cameras. They found $\log I_p/q = -12.96 \pm 0.14$ at $v = 32.2 \text{ kms}^{-1}$. By using this value of I_p/q Verniani (1964) has deduced for β the following value:

$$\beta = 0.010 \text{ at } v = 32.2 \text{ kms}^{-1}. \quad (28)$$

This seems a fairly reliable determination of β . It is 60 percent greater than the value given by eq. (23). Therefore, if we take into account that eq. (23) underestimates β , it is reasonable to adopt

$$\beta = 1 \times 10^{-20} v^4 \quad (29)$$

with an uncertainty in the exponent of about ± 0.3 . The uncertainty in the value of the constants is probably of the order of a factor of 2 essentially because of the present uncertainty in τ_p .

According to eqs. (2) and (29) we also obtain

$$\tau_q = 6 \times 10^{-13} v^2. \quad (30)$$

The determination of η from Whipple's method of comparing photographic and radio rates

Whipple (1955) showed that the following relation holds approximately

$$\log \tau_q / \tau_p = \text{const.} + \log \frac{N_r}{N_p} - \log v, \quad (31)$$

N_r and N_p being the observed numbers of radio and photographic meteors at velocity v . He compared the Harvard photographic small-camera meteors with McKinley's radio meteors (1951b) and found $\beta \sim v^5$. The average visual magnitude of the small-camera meteors is about -2, while that of McKinley's radio meteors can be estimated between +4 and +5.

This difference may be significant because of the systematic change in the average velocity of meteors with the magnitude found by Hawkins, Lindblad and Southworth (1963). At present McKinley's data are still the best source for evaluating N_r for radio meteors, because more recent radio data refer to meteors that are too faint to photograph. The photographic Super-Schmidt meteors reduced by Hawkins and Southworth (1958) are superior to the small-camera data because their average visual magnitude is about +3, close to that of McKinley's radio meteors. Moreover, they are a random sample. Following Whipple, we corrected the velocity distribution of the photographic meteors for seasonal variations (see Table 4); the curve of $\log N_r/N_p$ versus $\log v$ is given in Figure 2.

The least-squares solution for $\log N_r/N_p$ as a function of $\log v$ is

$$\log \frac{N_r}{N_p} = 9.96 + 2.17 \log v . \quad (32)$$

The standard deviation of the slope is about 0.6; thus we obtain $\beta \sim v^{4.2 \pm 0.4}$. Because of the uncertainties resulting from the observational effects on velocity, which are different in radio and in photographic meteors, the error in the value of η obtained with this method may be larger than ± 0.4 . Nevertheless the result is in reasonable agreement with the value $\eta = 4.0$.

Conclusions

On the basis of the preceding discussion we can accept expression (29) for β :

$$\beta = 1 \times 10^{-20} v^4 , \quad (29)$$

and for τ_v/β at $M_v = 0$ the equation:

$$(\tau_v/\beta)_{M_v=0} = 1 \times 10^{12} v^{-3} . \quad (33)$$

As a consequence, the relation (9) between the visual magnitude M_V and the electronic density q turns out to be independent of velocity, but the slope of the curve M_V vs. $\log q$ changes at $M_V = -2$ and at $M_V = +1.5$, since eq. (15) is valid only between these two limits. For $-2 < M_V < +1.5$ eq. (9) becomes:

$$M_V = 29.6 - 1.8 \log q . \quad (34)$$

Although τ_v depends on M_V , τ_p does not, so it appears much more convenient to relate the number of electrons to the photographic magnitude. The relation between M_p and I_p in physical units has been established (Davis and Hall 1963) as

$$M_p = 6.9 - 2.5 \log I_p ; \quad (35)$$

therefore,

$$M_p = 71.20 - 2.5 \log \tau_p / \beta - 7.5 \log v - 2.5 \log q . \quad (36)$$

According to Verniani (1964), independently of magnitude, we have

$$\tau_p = 5.25 \times 10^{-8} v , \quad (37)$$

and by substituting eqs. (29) and (37) into eq. (36) we eventually get

$$M_p = 39.40 - 2.5 \log q . \quad (38)$$

Equation (38) gives a relation between q and M_p valid for all velocities and magnitudes. As expected, eq. (38) agrees with the results of the measures of Davis and Hall, who found $\log q = 15.3 \pm 0.3$ for $M_p = +1.1 \pm 0.7$.

Also, the discrepancy (Hawkins and Southworth 1963) between the masses computed from photographic and radio data for a zero visual magnitude meteor is removed. The relation between the maximum electronic line density q_m and the initial mass m_∞ is given by

$$m_\infty = \frac{1}{12} \mu H f^{-2} (1 + 2f)^3 \frac{q_m}{\beta} \sec Z_R \quad (39)$$

(Weiss 1958, Verniani 1961), where $f = 1 + 3(2 + \eta) \xi v_\infty^{-2}$; ξ , the ablation energy of the meteor*; Z_R , the zenith angle of the meteor path; and H , the atmospheric scale height at the point of maximum ionization. A meteor having $M_V = 0$ has maximum ionization at about 90 km (Millman and McKinley 1963); at such an altitude H is equal to 5.56 km (U. S. Standard Atmosphere 1962). Therefore at $v = 40 \text{ kms}^{-1}$ and $\cos Z_R = 0.6$, equ. (39), (34) and (29) give $m_\infty \approx 0.8 \text{ gram}$. The same result was obtained from photographic data (Verniani 1964)

*For a solid body, $\xi = \gamma \frac{\ell}{\Lambda}$, where γ = drag coefficient, ℓ = latent heat of ablation for unit mass and Λ = heat-transfer coefficient. For ordinary crumbling meteors ξ is only the coefficient of the mass equation:

$$v = \frac{dv}{dt} = 2\xi m \frac{dm}{dt} \quad (40)$$

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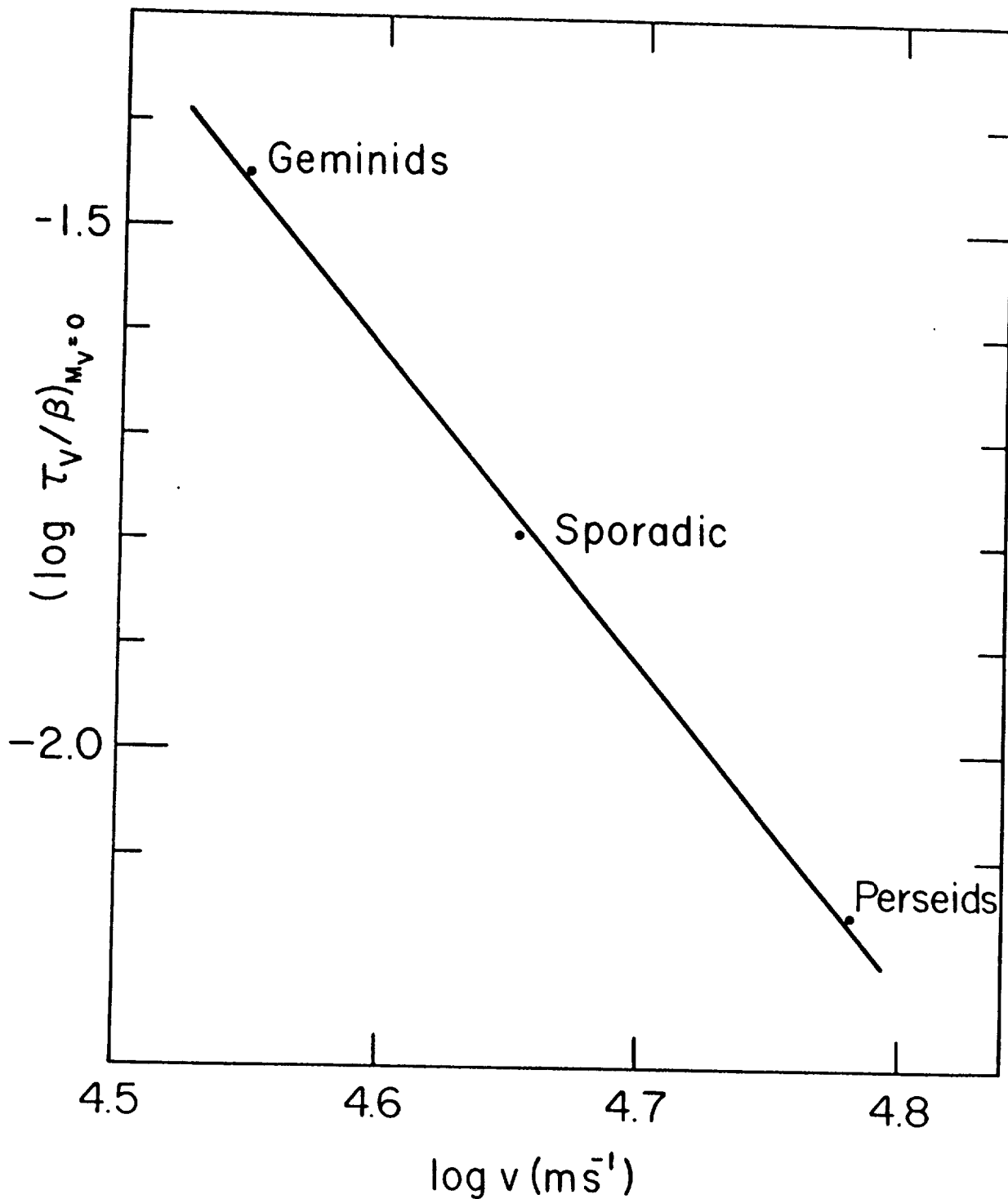


Figure 1.--The dependence of $(\log \tau_v/\beta)_{M_v=0}$ on the velocity. τ_v is the visual luminous efficiency and β , the ionizing probability. The results have been reduced to visual magnitude zero. The effect of attachment on the duration of echoes has been taken into account. Data from Millman and McKinley (1956).

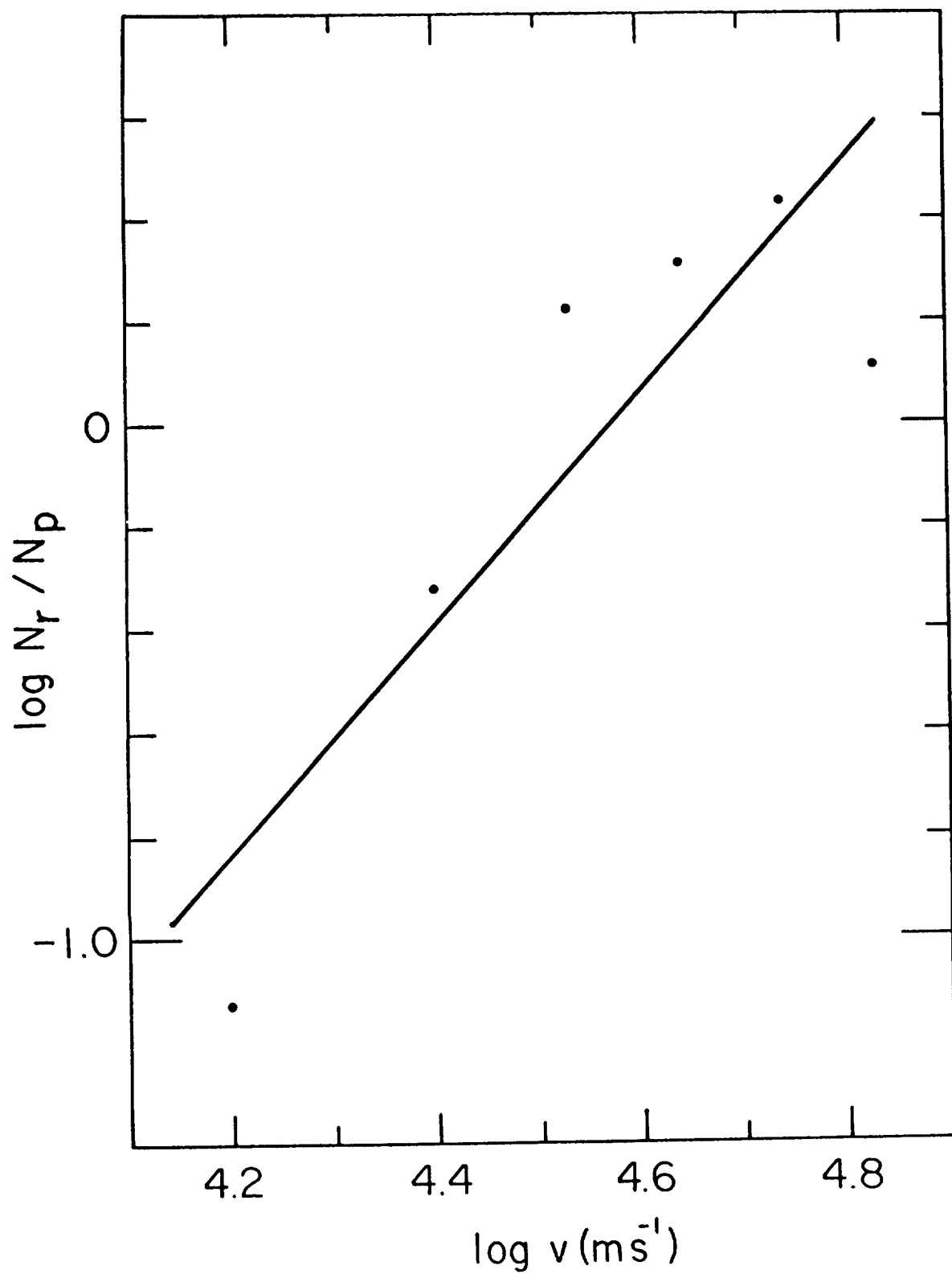


Figure 2.--Meteor frequency ratios plotted against velocities. Photographic data from Hawkins and Southworth (1958). Radio data from McKinley (1951b).

Table 1

The ionizing probability β_{Fe} for iron meteors according to Öpik (1958); β is the ionizing probability for cometary meteors deduced from Öpik's β_{Fe} , using Lazarus' and Hawkins' (1963) assumption that for each element $\beta \sim n_v \mu \Phi^{-6}$, where n_v = number of valence electrons available for ionization; μ = mean atomic mass; and Φ = ionization energy.

$v(\text{kms}^{-1})$	β_{Fe}	β
14.8	0.0025	0.00086
20.9	0.024	0.0083
29.6	0.071	0.024
41.8	0.134	0.046
59.2	0.207	0.071
83.6	0.297	0.102

The present results cannot be expressed in the form $\beta = \beta_0 v^{\eta}$; as a very rough approximation for comparison, however, one can assume for velocities between 20 and 60 kms^{-1} the equation $\beta \approx 2.10^{-11} v^2$.

Table 2

Summary of the previous estimates of the ionizing probability β .

Author	Year	β
Herlofson	1948	$\beta \approx 0.01$
McKinley	1951	$\beta \sim v^6$
Greenhow and Hawkins	1952	$\beta \approx 0.2$
Kaiser	1953	$\beta = 0.1 \div 1; \beta \sim v^{0 \pm 0.6}$
Evans and Hall	1955	$\beta \approx 0.1; \beta \sim v^{0.5 \pm 0.5}$
Whipple	1955	$\beta \sim v^5$
Hawkins	1956	$\beta \sim v^{5.6}$
Öpik	1958	$\beta \approx 2 \times 10^{-11} v^2$, see Table 1
Davis, Greenhow and Hall	1959	$\beta \sim v^{3 \pm 1}$
McKinley	1961	$\beta \sim v^5$
Davis and Hall	1963	$\beta = 0.03$ at $v = 32 \text{ kms}^{-1}$
Lazarus and Hawkins	1963	$\beta = 1.3 \times 10^{-19} v^{3.4}$
Verniani	1964	$\beta = 0.01$ at $v = 32 \text{ kms}^{-1}$
(This paper	1964	$\beta = 1 \times 10^{-20} v^{4.0}$)

Table 3

Basic data concerning average magnitude and echo duration, height and velocity for Perseids, Geminids and sporadic meteors (Millman and McKinley 1956).

	No.	Mean velocity kms^{-1}	Mean height km	Mean magnitude M_V	Average log T (T = duration, s)	Average log T_D (T_D duration corrected for attachment, s)
Perseids	1404	60.5	99.3	+0.40	0.710	0.785
Geminids	256	35.3	91.6	+0.78	0.919	0.988
sporadic	1420	45*	94*	+1.22	0.595	0.637

* Data from McKinley (1961) referring to the same meteors.

Table 4

Meteor velocity distributions: radio meteors from McKinley (1951b)
and photographic meteors from Hawkins and Southworth (1958).

Velocity range 10^3 ms^{-1}	$\log v$ ms^{-1}	N_r percent	N_p percent	$\log N_r/N_p$
10-20	4.20	1.8	24.2	-1.13
20-30	4.40	12.7	26.6	-0.32
30-40	4.53	27.9	16.8	0.22
40-50	4.64	19.8	9.6	0.31
50-60	4.74	16.8	6.3	0.43
> 60	4.83	21.0	16.5	0.11

